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FEEDBACK LIMITS RAPID GROWTH OF SEED BLACK HOLES AT HIGH REDSHIFT

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ABSTRACT

Seed black holes formed in the collapse of population III stars have been invoked to explain the presence of supermassive black holes at high redshift. It has been suggested that a seed black hole can grow up to $10^{5\sim6}M_\odot$ through highly super-Eddington accretion for a period of $\sim 10^{6\sim7}$ yr between redshift $z = 20 \sim 24$. We studied the feedback of radiation pressure, Compton heating and outflow during the seed black hole growth. It is found that its surrounding medium fueled to the seed hole is greatly heated by Compton heating. For a super-critical accretion onto a $10^3M_\odot$ seed hole, a Compton sphere (with a temperature $\sim 10^6$K) forms in a timescale of 1.6×10^3yr so that the hole is only supplied by a rate of 10^{-3} Eddington limit from the Compton sphere. Beyond the Compton sphere, the kinetic feedback of the strong outflow heats the medium at large distance, this leads to a dramatical decrease of the outer Bondi accretion onto the black hole and avoid the accumulation of the matter. The highly super-critical accretion will be rapidly halted by the strong feedback. The seed black holes hardly grow up at the very early universe unless the strong feedback can be avoided.

Subject headings: cosmology: theory – black holes – galaxies: evolution

1. INTRODUCTION

Black holes are regarded as an extremely important population in modern cosmological physics. The reionization of the Universe may get started from $z \sim 17$ deduced from *Wilkinson Microwave Anisotropic Probe* (*WMAP*) which gives Thomson scattering depth $\tau = 0.17 \pm 0.04$ (Spergel et al. 2003). Such an early reionization epoch needs a large population of seed black holes collapsed from population III stars (Madau et a. 2004). Second, the discovery of the currently known highest redshift quasar, SDSS 1148+3251 at $z = 6.4$ (roughly 1 Gyr) from *Sloan Digital Sky Survey* (SDSS; Fan et al. 2001) indicates that there are already supermassive black holes with $M_{\rm BH} > 10^9M_\odot$ (Netzer 2003, Barth et al. 2003, Willott et al. 2003). What is the relation between the seed and supermassive black holes? How to form supermassive black holes?

Rees' diagram shows several possible ways to form supermassive black holes (Rees 1984). A direct collapse of primordial clouds could form supermassive black holes after cosmic background radiation photons remove enough angular momentum through Compton drag (Loeb 1993, Loeb & Rassio 1994). This scenario is favored by Lyα fuzz of the extended emission in quasar where the supermassive black hole has been formed and the galaxy is assembling (Weidinger, Moller & Fynbo 2004), especially the recent discovery of an isolated black hole of the quasar HE 0450-2958 without a massive host galaxy (Magain et al. 2005). Second, a rapid growth of a seed black hole with highly super-Eddington accretion rates is used to explain the existence of the black hole $> 10^9M_\odot$ at high redshift. Third a compact cluster of main sequence stars, or neutron stars/black holes will inevitably evolve into a supermassive black hole (Duncan & Shapiro 1983, Quinlan & Shapiro 1990), and this gets supports from the quasar's metallicity properties (Wang 2001). The different ways to form a supermassive black hole may apply to different redshifts or environments.

A rapid growth of seed black holes is quite a promising model to issue the formation of supermassive black holes at redshift $z \sim 6$ (Volonteri & Rees 2005). The Bondi accretion rate is $\dot{m} = \dot{M}_{\rm Bondi}/\dot{M}_{\rm Edd} \sim 40$, where $\dot{M}_{\rm Edd} = L_{\rm Edd}/c^2$ and $L_{\rm Edd}$ is the Eddington limit, for a $10^3M_\odot$ black hole surrounded by medium cooled by the hydrogen atomic lines. The seed black hole is able to grow up exponentially $M_{\rm BH} = M_0\exp(\dot{m}t/t_{\rm Salp})$, where the Salpeter timescale $t_{\rm Salp} = 0.45$Gyr. However, such a high accretion rate inevitably gives rise to strong interactions of radiation and outflows with the Bondi accretion flow. Consequently, the strong feedback seriously constrains the matter supply to the black hole, even stops the accretion.

In this Letter we discuss how the feedback impacts on the growth of the seed black holes. We find they can not grow up between redshift $z = 20 \sim 24$ through accretion. The implications of the present results are discussed.

2. GROWTH: FEEDBACK LIMIT

2.1. *Angular momentum and accretion onto seed black holes*

The very first population III stars rapidly evolve into intermediate mass black holes (IMBHs), $20 < M_{\rm BH}/M_\odot < 70$ and $130 < M_{\rm BH}/M_\odot < 600$ (Fryer et al. 2001, Omukai & Palla 2003). These IMBHs, as shown in Volonteri & Rees (2005), can rapidly grow up to supermassive black holes via Bondi accretion with a super-critical rate.

The strong tidal torque due to nearby clouds efficiently offer angular momentum J to each other (Peebles 1969, Barnes & Efstathiou 1987). For a rigid virialized sphere with mass M, total energy E and radius R, its angular momentum is characterized by $J_0 = GM^{5/2}/|E|^{1/2}$, where G is the gravitational constant (Peebles 1969). It is useful to define a dimensionless parameter, $\lambda \equiv J/J_0 = J|E|^{1/2}G^{-1}M^{-5/2}$, for a cloud with mass M, angular momentum J and the total energy E. Following Oh & Haiman (2002), a cold fat disk is formed with an isothermal exponential radial distribution

$$n(R,h) = n_0\exp\left(-\frac{2R}{R_d}\right)\sec^2\left(\frac{h}{\sqrt{2}H_0}\right), \qquad (1)$$

where n_0 and H_0 are the central density and vertical scale height of the disk at radius R, R_d is the radial scale length. The central

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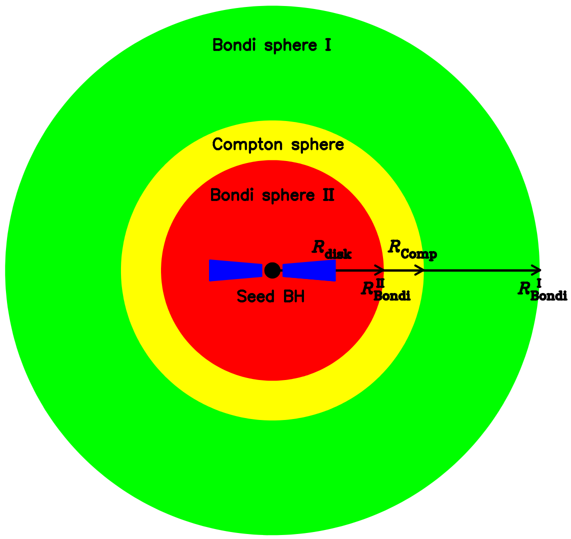

FIG. 1.— The scenario of a growing seed black hole. A tiny accretion disk is formed since the accreting matter has angular momentum. The feedback from the tiny disk has strong influences on its surrounding, leading to shrink the Bondi accretion radius and dramatic decreases of Bondi accretion rate since the sound speed increases. The outflow developed from the disk has strong influences on the region beyond the Bondi sphere I. The super-Eddington accretion is suddenly suppressed and the growth of the seed black hole stops (see detail in the text).

density is given by

$$n_0 \approx 6\times 10^4 f_{d,0.5}^2\ \lambda_{0.05}^{-4}\left(T_3/8\right)^{-1} R_{\rm vir,6}^{-4} M_{\rm H,9}^2 \quad {\rm cm}^{-3}, \qquad (2)$$

where $f_{d,0.5}=f_d/0.5$ is the gas fraction settled into the isothermal disk, $\lambda_{0.05}=\lambda/0.05$, $T_3=T/10^3$K, $R_{\rm vir,6}=R_{\rm vir}/6$kpc and $M_{\rm H,9}=M_{\rm H}/10^9M_\odot$ are the virialized radius and mass of the halo, respectively. The disk's radius scale is $R_d\sim\lambda R_{\rm vir}/\sqrt{2}$.

The Bondi accretion radius of the seed black hole is

$$R_{\rm Bondi}^{\rm I} = 1.4\times 10^9 R_{\rm G}\ m_3\left(T_3/8\right)^{-1}, \qquad (3)$$

where $m_3=M_{\rm BH}/10^3M_\odot$, $R_{\rm G}=GM_{\rm BH}/c^2$ and c is the light speed. $R_{\rm Bondi}^{\rm I}$ is much smaller than the vertical scale of the cold fat disk. This means that the density within Bondi accretion radius is almost constant with a quasi-spherical geometry. As argued by Volonteri & Rees (2005), the transverse velocity at the Bondi radius ($R_{\rm Bondi}^{\rm I}$) is of the order of $\left(R_{\rm Bondi}^{\rm I}/R_d\right)v_{\rm D}$, where $v_{\rm D}$ is the rotation velocity of the fat gas disk at R_d. Due to the specific angular momentum of the quasi-Bondi flow, a tiny disk will form within $R_{\rm Bondi}^{\rm I}$. Figure 1 shows a cartoon of the present case with feedback. Assuming conservation of the specific angular momentum within $R_{\rm Bondi}^{\rm I}$, we have the outer radius of the tiny accretion disk

$$R_{\rm disk} = 6\times 10^2 R_{\rm G}\ v_{\rm D,10}^2 m_3^2 \lambda_{0.05}^{-2} R_{\rm vir,6}^{-2}, \qquad (4)$$

where $v_{10}=v/10{\rm km\ s^{-1}}$, which is much smaller than the Bondi accretion radius. The quasi-sphere flow will switch on the tiny disk with a Bondi accretion rate, given by $\dot{M}_{\rm Bondi}=\gamma 4\pi n m_p\left(GM_{\rm BH}\right)^2/c_s^3$ (Bondi 1952)

$$\frac{\dot{M}_{\rm Bondi}^{\rm I}}{\dot{M}_{\rm Edd}} = 188\ \gamma m_3 (n_4/4)(T_3/8)^{-3/2}, \qquad (5)$$

where c_s is the sound speed, m_p is the proton mass, γ is a dimensionless constant of order unity and $n_4=n/10^4{\rm cm}^{-3}$. The tiny accretion disk with such a high rate is characterized by photon-trapping self-similar structure within trapping radius, where the photon escaping timescale from the disk is equal to that of the radial moving to the black hole (Begelman & Meier 1982, Wang & Zhou 1999, Ohsuga et al. 2003). We note that the disk radius ($R_{\rm disk}$) is comparable to the photon trapping radius $R_{\rm tr}\approx 3.2\times 10^2 R_{\rm G}\left(\dot{m}/180\right)$ (Wang & Zhou 1999), indicating that the entire tiny disk may be advection-dominated via photon trapping process. According to the self-similar solution of the optically thick advection-dominated accretion flow (Wang & Zhou 1999), the radiated luminosity is only a small fraction of the released gravitational energy via viscosity dissipation

$$L_{\rm Bol}\approx 4.0\times 10^{40} m_3\left[1+\frac{1}{4}\ln\left(\frac{\dot{m}}{180}\right)\right] \quad {\rm erg\ s^{-1}}, \qquad (6)$$

where we have used the photon trapping radius $R_{\rm tr}$ implied above. This is a saturated luminosity weakly dependent on the accretion rate. The total released luminosity is given by $L_{\rm grav}=1.4\times 10^{42}(\eta/0.1)\left(\dot{m}/10^2\right) m_3$ erg s^{-1} , most of them are advected into the black hole.

The emergent spectrum from the slim disk is characterized by a universe shape of $F_\nu\propto\nu^{-1}$ (Wang & Zhou 1999, Wang et al. 1999, see also Shimura & Manmoto 2003, Kawaguchi 2003), the hard X-ray emission is highly dependent on the factor f, which indicates how many energy is released in the hot corona (Wang & Netzer 2003, Chen & Wang 2004, hereafter, Socrates & Davis 2005). Even $f=1\%$, the released energy from hot corona is close to Eddington limit. The physics related with the factor f remains open. The Compton temperature reads $T_{\rm C}=\langle\epsilon\rangle/4k$, where k is the Boltzmann constant and $\langle\epsilon\rangle$ is the mean energy of photons from the disk which depend on F_ν. The mean energy of the photons are in a range of $0.4\sim 10$keV for $f=0.01\sim 0.025$ (Wang & Netzer 2003). We take the lower value $\langle\epsilon\rangle=0.4$keV, so the medium will be heated up to $T_C\approx 10^6$K at least. It should be pointed out that the higher the Compton temperature is, the stronger the feedback from the tiny accretion disk has influence on its surroundings.

2.2. *Feedback: radiation pressure and Compton heating*

The radiation pressure acting on the medium inside the Bondi accretion sphere is of order $P_{\rm rad}\sim\tau_{\rm es}L/4\pi R^2c$, where the Thomson scattering depth is $\tau_{\rm es}=Rn\sigma$ and σ is Thomson cross section. We find the ratio of $P_{\rm rad}/P_{\rm gas}=L\sigma/4\pi RckT$, beyond the radius $R_R=8.5\times 10^7 R_{\rm G}\ L_{40}T_4^{-1}m_3^{-1}$, the radiation pressure is negligible, where $T_4=T/10^4$K. Since the photon trapping effects, the radiated luminosity from the highly super-critical accretion disk is lower than Eddington limit by a factor of 3 (see equation 6). So radiation pressure hardly prevents the infalling matter from accretion onto the black hole. The feedback from the radiation pressure is negligible.

The Bondi flow will be heated by the radiation from the tiny accretion disk. In turn, the heated medium determines a new Bondi accretion rate switched on the tiny disk. The thermal status of the photoionized medium can be conveniently described by the ionization parameter defined as $\Xi=L/4\pi R^2cnkT$ (Krolik, McKee & Tarter 1981). We focus on a region with $\Xi\ge\Xi_{\rm C}=1.1\times 10^3 T_{C,6}^{-3/2}$ (for pure hydrogen gas), here $T_{C,6}=T_C/10^6$K, where the entire medium will be heated up to Compton temperature T_C. It follows from

$$R_{\rm Comp}^{\Xi}=\left(\frac{L}{4\pi c\Xi_c nkT}\right)^{1/2} = 2.8\times 10^8 R_{\rm G}\ L_{40}^{1/2} n_4^{-1/2} T_4^{-1/2} m_3^{-1}, \qquad (7)$$

which is called the Compton radius (and sphere). It needs a Compton timescale $t_C=6\pi m_e c^2 R_{\rm Comp}^{\Xi^2}/\sigma L\sim 1.3\times 10^5$yr to

form such a Compton sphere. However the Compton sphere is also constrained by the balance of the heating and infalling timescale of the Bondi flow. It follows from $t_C = t_{\rm infall}$,

$$R^{\rm infall}_{\rm Comp} = \frac{\sigma L}{6\pi m_e c^2 \beta_s c_s} = 3.1\times 10^7 R_{\rm G}\ \beta_{s,0.1}^{-1} L_{40} T_4^{-1/2} m_3^{-1} \quad (8)$$

where $\beta_s = v_R/c_s$ is the infalling velocity of the Bondi flow normalized by the sound speed and $\beta_{s,0.1} = \beta_s/0.1$. The effects of the infalling on the Compton sphere can be neglected if the infalling velocity is less than $\beta_s \le 10^{-2}$. For $\beta_s = 0.1$, we find $R^{\Xi}_{\rm Comp} > R^{\rm infall}_{\rm Comp}$. This means that *not* entire region with $\Xi > \Xi_c$ can be heated up to the Compton temperature (T_C). So the Compton radius is given by $R_{\rm Comp} = \min\left(R^{\Xi}_{\rm Comp}, R^{\rm infall}_{\rm Comp}\right) = R^{\rm infall}_{\rm Comp}$, corresponding to a timescale of 1.6×10^3yr. We note that $R_{\rm Comp} < R^{\rm I}_{\rm Bondi} \ll R_d \approx 0.2\lambda_{0.05} R_{\rm vir,6}$ kpc.

Within the Compton sphere, the seed black hole has a new Bondi accretion radius

$$R^{\rm II}_{\rm Bondi} = \frac{GM_{\rm BH}}{c_s^2} = 1.1\times 10^7 R_{\rm G}\ T_6^{-1}, \quad (9)$$

and a Bondi accretion rate,

$$\frac{\dot M^{\rm II}_{\rm Bondi}}{\dot M_{\rm Edd}} = 0.13\ m_3 (n_4/4) T_6^{-3/2}. \quad (10)$$

We note that this radius is still much larger than the tiny disk $R_{\rm disk}$ and this accretion rate is much smaller than that in the pre-feedbacked. The timescale of the Compton heating at $R^{\rm II}_{\rm Bondi}$ is $t_C = 2.0\times 10^2$yr. That is to say the beginning Bondi accretion will be halted suddenly. After the termination of the super-critical accretion, the hot plasma in Bondi sphere II will be cooled at a timescale of $1.8\times 10^4 n_{C,2}^{-1} T_{C,6}^{1/2}$yr via free-free emission, where $n_{C,2} = n_C/10^2{\rm cm}^{-3}$ and $T_{C,6} = T_C/10^6$K. Therefore it is expected that there is a steady accretion onto the seed black hole, but with a sub-Eddington rate, which is self-regulated.

When the Compton sphere forms, the pressure balance with its surroundings should hold, we have $n_C kT_C = n_0 kT_0$, where the subscript "C" and "0" represent Compton sphere and its pre-feedbacked surroundings, respectively. So we can get the Bondi accretion rate $\dot M^{\rm II}_{\rm Bondi}$ inside the Compton sphere in the form of n_0 and T_0,

$$\frac{\dot M^{\rm II}_{\rm Bondi}}{\dot M_{\rm Edd}} = 1.3\times 10^{-3} m_3 (n_{0,4}/4) T_{0,4}^{-3/2}, \quad (11)$$

where $n_{0,4} = n_0/10^4{\rm cm}^{-3}$ and $T_{0,4} = T_0/10^4$K. With such a low accretion rate, the seed black hole can not grow significantly.

Since $\dot M^{\rm I}_{\rm Bondi} \gg \dot M^{\rm II}_{\rm Bondi}$, the accretion onto the black hole from the Bondi sphere I is continuing, then the matter will pile up between the region of $R^{\rm II}_{\rm Bondi} \le R \le R^{\rm I}_{\rm Bondi}$. Such a dense shell will collapse when pressures are not powerful enough to balance it. Thus the accretion onto the seed black holes could be pulsive with a period. However, the oscillating accretion will be avoided if the outflow is supplied.

2.3. *Feedback: outflow*

Wind/outflow is a generic property of the accretion disk. There are many pieces of evidence for the presence of strong outflows from accretion disks. In the quasar PG 1211+143, the outflow is indicated by the blueshifted X-ray absorption lines with a velocity of $0.1c$ and has an outflow mass rate $\dot M_{\rm out} \sim 1.6 M_\odot$/yr (Pounds et al. 2003). Similar strong outflows are found in ultraluminous X-ray sources (Mukai et al. 2003, Fabbiano et al. 2003) and SS 433 which clearly has strong outflows ($> 5\times 10^{-7} M_\odot{\rm yr}^{-1}$) from the highly super-critical accretion disk (Kotani et al. 1996). A strong outflow is expected to develop from the tiny accretion disk, leading to efficient kinetic feedback to its surroundings. Here we neglect the detailed micro-physics of the interaction between outflow and medium. The kinetic luminosity is given by $L_{\rm kin} \approx (\dot m f_m \beta^2) L_{\rm Edd} \approx L_{\rm Edd}$, where f_m is the fraction of the outflow to the accretion rate and we take $\dot m f_m \beta^2 = 1$. The simple energy budget can provide a rough estimation of the outflow kinetic energy. When the outflow is damped by its surroundings, its most kinetic energy will dissipate at the sonic radius

$$R_{\rm Sonic} \approx 1.0{\rm pc}\ L_{40}^{1/2} (n_4/6)^{-1/2} T_{0.1}^{-1/4}, \quad (12)$$

where $T_{0.1} = T/0.1$keV is the temperature of the surroundings (Begelman 2004). This radius is much smaller than the characterized radius of the fat disk ($R_d \sim 0.2$kpc), but it is comparable to the inner quasi-spheric part of the cold fat disk. The kinetic luminosity ($L_{\rm kin}$) can compensate the free-free radiation loss of the hot plasma within the radius $R_{\rm Sonic}$. For a typical outflow, the timescale of reaching the sonic point is $R_{\rm Sonic}/\beta c \approx 30(\beta/0.1)$yr. It would be interesting to note that this feedback timescale is much shorter than the Compton heating in the present case. We could draw a conclusion that the kinetic feedback from the outflow does play an important role in the growth of the seed hole.

On the other hand, the mass loss through the strong outflow definitely prevents the seed holes from growth. However the mass rate of the outflow is uncertain, we do not know exactly how the growth of the seed holes is affected via mass loss.

Finally, we would like to point out that we use the self-similar solutions of the super-Eddington accretion (Wang & Zhou 1999) based on the slim disk (Abramowicz et al 1988). The super-critical accretion remains a matter of debate since there are several instabilities, especially the photon bubble instability (Gammie 1998). The instability results in inhomogeneity of the disk, allowing the trapped photons to escape from the disk and enhance the disk radiation. If we employ the radiation leakage model at a level of $L_{\rm Bol} \sim 300 L_{\rm Edd}$ (Begelman 2002), the feedback will be much stronger than we have discussed above. Thus the results from the present paper is a lower limit of feedback.

3. DISCUSSIONS

For simplicity, we assume the radiation is isotropic from the tiny accretion disk. The anisotropic radiation from the slim disk could suppress the Compton heating in some degrees. The self-similar solution gives the ratio of the height to the radius $H/R = (5+\alpha^2/2)^{-1/2} \approx 0.45$, where α is the viscosity parameter (Wang & Zhou 1999). The half-opening angle is about $\theta \approx 66^\circ$, the radiation will be confined within $1-\cos\theta \approx 60\%$ of the 4π solid angle. This assumption is reasonable. However the anisotropic radiation from the tiny disk may lower the feedback of the Compton heating. Future work will consider how the anisotropy effects the feedback for a time-dependent situation, which is beyond the scope of the present paper.

There are other possible ways to form supermassive black holes. The direct collapse of primordial clouds in which the angular momentum is removed by the cosmic background photons (Loeb 1993, Loeb & Rassio 1994) can form a $10^6 M_\odot$ black hole at $z \sim 15$. If the seed black hole accrets dark matter, its growth is not suffering from the strong feedback (Hu et al.

2005). The inevitable fate of a compact cluster is the formation of a supermassive black hole (Quinlan & Shapiro 1990). These possible ways might apply to different environments in the universe, it depends on future observations to test them.

4. CONCLUSIONS

We show that the feedback of the radiation pressure, Compton heating and outflows from the super-critical accretion disks will result in strong influence on the accretion itself. We show that the Compton heating almost quenches the super-critical accretion and the outflow from the tiny disk heats up the outer region so that accumulation of matter is avoided. A rapid growth of seed black holes is greatly suppressed and they are hardly able to grow up unless the strong feedback can be avoided, for example considering the anisotropy of the radiation from the tiny accretion disk.

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